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# The design features of the HTR-10

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**Abstract**

The 10 MW High Temperature Gas-cooled Test Reactor (HTR-10) is a modular pebble bed type reactor. This paper briefly introduces the main design features and safety concept of the HTR-10. The design features of the pebble bed reactor core, the pressure boundary of the primary circuit, the decay heat removal system and the two independent reactor shutdown systems and the barrier of confinement are described in this paper. © 2002 Elsevier Science B.V. All rights reserved.

## 1. Introduction

The 10 MW High Temperature Gas-cooled Test Reactor (HTR-10) is a modular pebble bed type reactor.

The Modular High Temperature Gas-cooled Reactor concept was proposed originally as the 'HTR-Module' by Siemens German in 1979. The most important design features are as follows (Lohnert, 1990):

- The use of spherical elements, which are capable of retaining all radiologically relevant fission products up to fuel element temperatures of approx. 1600 °C.
- The reactor core is designed and laid out such that a maximum fuel element temperature of 1600 °C is not exceeded during any accident.
- Active core cooling is not necessary for decay heat removal during accidents. It is quite sufficient to discharge the decay heat by means of passive heat transport mechanisms (such as heat conduction, radiation, nature convention) to a simple cavity cooler outside the reactor pressure vessel.
- Reactor shutdown is carried out solely by absorber elements, which, on demand, can drop freely into borehole of the reflector.
- Graphite is used in core areas with high temperatures (fuel elements, core internals). Temperature-incurred failure of these materials is impossible at the maximum occurring temperature of 1600 °C.
- The noble gas helium, which is neutral from a chemical and neutron physical viewpoint, is used as coolant.
- Due to the high activity retention of the fuel elements, a pressure-tight reactor building is not necessary. The reactor building is accessible for repair work at any time after an accident as a result of the low activity release.

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- Reactor core and steam generator are installed in separate steel pressure vessels in such a way that there is no danger of components overheating in the case of failure of primary circuit cooling. This chosen installation also increases the accessibility of the components for maintenance and repair.

The cross-section through the primary system of Siemens HTR-Module is shown in Fig. 1.

Those principle features of the HTR-Module are also applied to the HTR-10 design (Steinwarz and Yuanhui, 1990). The HTR-10 is designed for co-generation of electricity and district heating with 10 MW thermal power. The important goal of the HTR-10 design is to demonstrate the inherent safety features of the Modular HTGR.

The Modular HTGR is well known for its excellent safety in terms of the following features:

- Capacity of retaining all fission products in the coated particles up to the temperature of 1600 °C.

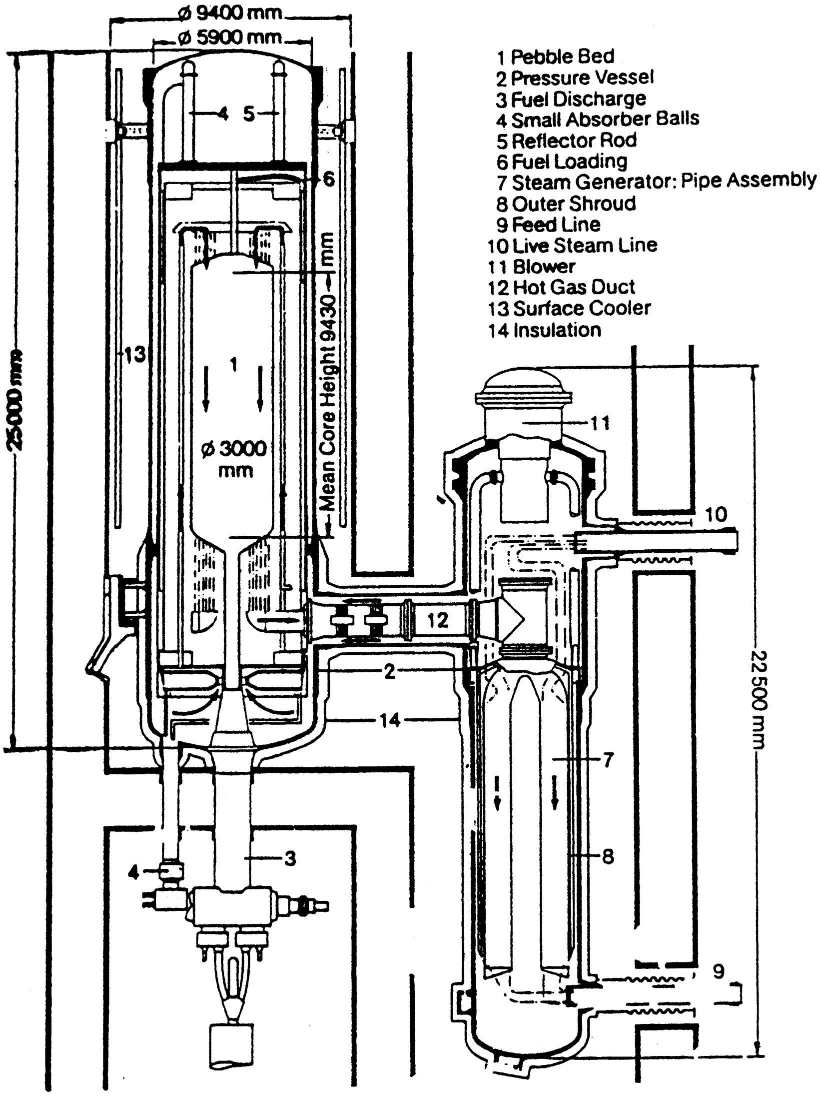


Fig. 1. Cross section of the HTR-module.

- Large fuel temperature margin and negative temperature reactivity coefficient sufficient to accommodate reactivity insertion.
- Large heat capacity of the core to mitigate temperature transition.
- Small amount of excess reactivity in the core.
- Passive decay heat removal.

The core of the HTR-10 is formed as a pebble bed with 27 000 spherical fuel elements. The pebble bed reactor is considered for its merit of continuous discharge of spherical fuel elements, which can increase the reactor operation availability.

Spherical fuel elements with 'TRISO' coated particles are used in the HTR-10. The $UO_2$ fuel kernel of particles is coated by ceramic layers, namely the inner buffer layer with less dense pyro-carbon, the dense pyro-carbon, the SiC coating and the outer layer of dense pyro-carbon. A spherical fuel element of 60 mm diameter is composed of an inner zone of 50 mm diameter and 5 mm thick shell of fuel free zone and about 8000 coated fuel particles are dispersed in the graphite matrix of the inner zone.

In any severe accident conditions the decay heat of the HTR-10 could be transferred and dissipated into the atmosphere via the passive decay heat removal system. The maximum temperature of the fuel should not exceed the temperature limit of 1600 °C, below which the SiC layer could retain the fission products within the particles, in the accident transients. Therefore the core damage accidents could be excluded in the Modular HTGR.

In terms of the requirement of HTR-10, the fraction of uncoated free uranium content of the fuel elements should be less than $8 \times 10^{-4}$ during manufacture and irradiation. Then the gaseous fission products of the uncoated free uranium could be released into the primary coolant system and the helium purification system would remove most of the fission products from the primary coolant and maintain the concentration of fission products in the primary coolant at a low level. Once the accidents of pipe rupture have happened, the loss of coolant and depressurization will occur and the fission products in the primary coolant will be released into the atmosphere. The accident analyses indicate that the impact of the radioactivity release on the environment would be much lower than the regulatory limits set for the HTR-10.

Table 1
The major design parameters of the HTR-10 test reactor

| Item | Unit | Value |
|---|---|---|
| Thermal power | MW | 10 |
| Reactor core diameter | cm | 180 |
| Average core height | cm | 197 |
| Primary helium pressure | MPa | 3.0 |
| Average helium temperature at reactor inlet/outlet | °C | 250/700 |
| Helium mass flow rate at full power | kg $s^{-1}$ | 4.3 |
| Average core power density | MW $m^{-3}$ | 2 |
| Power peaking factor | | 1.54 |
| Number of control rods in side reflector | | 10 |
| Number of absorber ball units in side reflector | | 7 |
| Nuclear fuel | | $UO_2$ |
| Heavy metal loading per fuel element | g | 5 |
| Enrichment of fresh fuel element | % | 17 |
| Number of fuel elements in core | | 27 000 |
| Fuel management | Multi-pass | |
| Average residence time of one fuel element in core | EFPD | 1080 |
| Max. power rating of fuel element | kW | 0.57 |
| Max. fuel temperature (normal operation) | °C | 919 |
| Max. burn-up | MWd $tHM^{-1}$ | 87 072 |
| Average burn-up | MWd $tHM^{-1}$ | 80 000 |
| Max. thermal flux in core ($E$ > 1.86 eV) | n $cm^{-2}$ $s^{-1}$ | $3.43 \times 10^{13}$ |
| Max. fast flux in core ($E$ > 1 MeV) | n $cm^{-2}$ $s^{-1}$ | $2.77 \times 10^{13}$ |

Table 1 lists the key design parameters of the HTR-10 test reactor.

## 2. Pebble bed reactor core

The reactor core of HTR-10 contains about 27 000 spherical fuel elements of 6 cm diameter, which form a pebble bed of 180 cm in diameter and 197 cm in average height. The mean power density of the core is 2 MW $m^{-3}$.

The fuel elements drop into the reactor core from the central fuel charging tube and pile up at the top of the core. The space of 40 cm height between the top of the core and the bottom of upper graphite reflect is a margin for accommodating the criticality calculation uncertainty. The fuel elements move downward in the reactor core and discharge through a tube of 50 cm inside diameter at the core bottom and a connected singularizer, after which the fuel elements are lined up and then pass the defective fuel separator and the burn-up measurement facility one by one.

The defective fuel elements and the scrap fragments should be sorted out and dropped into the scrap container. The fuel elements, which have not reached the burn-up target, will be re-circulated into the reactor core, and the spent fuel elements exceeding the burn-up target will be discharged and transported into the spent fuel storage tank, depending the burn-up measurement. New fuel elements are loaded into the core in a special charging facility in which the atmospheric isolation is realized to prevent air penetrating into the primary system and coolant being released into the environment. Transport of fuel elements in the fuel handling system is by means of pneumatic force and gravity.

In order to reduce the power peaking factor of the HTR-10 core the fuel management is utilizing a 'multi-pass' scheme. Each fuel element will pass through the reactor core five times in average before it reaches the burn-up target.

The upper, side and bottom graphite reflectors surround the reactor core. Each layer of the side reflector consists of 20 segmental graphite bricks in which ten control rod channels; seven absorber ball channels and three experimental channels are drilled. In addition, 20 cold helium channels are located in each layer of the side reflector to reduce the graphite temperature under operating condition, and to mitigate the temperature rising of fuel elements under accident condition due to the large heat capacity of the graphite structure. The bottom structure of the core is designed to be a conical section with an 30° angle to facilitate free movement of the fuel elements by gravity. The heated helium gas flows through the channels in the bottom reflector graphite bricks and into the hot gas chamber, and then out of the reactor vessel through the hot gas duct, which is connected with the pressure vessel of the steam generator. In order to avoid a 'crystallization' of the fuel elements as they move along the internal wall surface, the inner surface of the side reflector is provided with dish-like indentations, which guarantee the pebble flow.

The boronated carbon bricks surround the graphite reflector. The carbon and boronated carbon bricks play roles of thermal insulation to reduce the heat loss as well as neutron shielding to protect the metallic internal structure and the reactor pressure vessel.

The graphite and carbon bricks are connected vertically with a dowel and a dowel socket system, and horizontally with the key and the keyway system to insure the stability and integrity of the core structure and to prevent helium gas from leaking through the gaps between graphite columns. The dowels and keys are made from graphite material. The full ceramic internal is supported on the lower support plate of the metallic internal structure, and connected with the core vessel by the metallic keys.

The bottom of the metallic internal structure is supported on the inside flanges of the reactor pressure vessel wall by ten rolling bearings. The metallic internal structure will be displaced caused due to thermal expansion relative to the reactor pressure vessel caused by changing of the reactor temperature. The cross section of the reactor structure of the HTR-10 is shown in Fig. 2.

The HTR-10 uses helium gas as coolant, which has thermal and chemical stability, good compatibility with the core graphite material and metallic material of the primary system at high temperature condition; in addition, there is no phase transition. The cold helium at inlet temperature of 250 °C flows through the pebble bed core from the top to the bottom, and is heated up to 700 °C. The maximum temperature of the fuel elements appears in the bottom section of the reactor core under normal operating condition. The average burn-up of fuel elements in bottom section is higher than that of the whole reactor core. Therefore, both the helium gas and the fuel elements flow in down direction are helpful to reduce the maximum fuel temperature under normal operating conditions.

## 3. The side by side arrangement of the reactor pressure vessel and the steam generator vessel

The pressure boundary of the HTR-10 primary circuit consists of the reactor pressure vessel, the steam generator pressure vessel and the hot gas duct vessel. The side by side arrangement of the reactor pressure vessel and steam generator vessel has the following advantages: (1) making the maintenance of the steam generator and the main helium circulator convenient; (2) reducing the probability of the core water ingress after rupture of steam generator tubes.

The steam generator and the main helium circulator are installed together in one pressure vessel. The steam generator is of the once through type

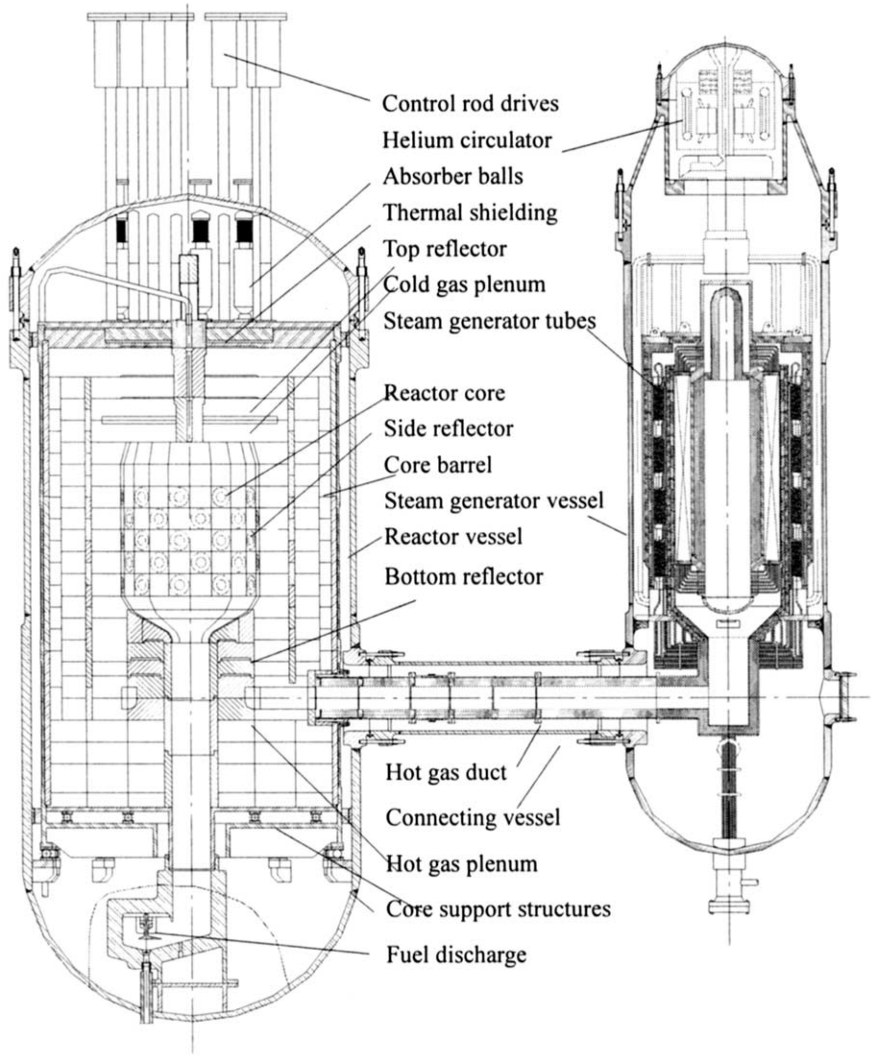


Fig. 2. The HTR-10 reactor and steam generator arrangement in the primary cavity.

and consists of 30 helical tube bundle modules. Each module consists of a small helical tube bundle, which has a diameter of 112 mm. The material of the heat transfer tubes is 2(1/4) Cr-1Mo and its maximum design temperature is 500 °C. The tube diameter is changed in different heat transfer sections and the throttles orifices are installed in the inlet of feed water connection tubes to improve the hydrodynamic stability of steam-water two phase flow and to insure the flow stability at operating power above 30% of the nominal power.

The main helium circulator is a vertical single-stage centrifugal one with an impeller at the lower end of the shaft. The drive motor is assembled on the upper section of the same shaft. The bearings are lubricated by grease. The speed of the motor is adjustable by a power frequency converter. An isolation valve is installed on the inlet tube of the circulator. It can be closed automatically also circulator shutdown. This avoids helium natural convection in the primary circuit and prevents the temperature of the pressure vessels exceeding its design limit value due to hot helium flowing backwards through the pressure vessels.

The helium routing of the primary circuit is such as to insure the pressure boundary staying at low temperature. Therefore, all three steel pressure vessels (the reactor vessel, steam generator vessel and hot gas duct vessel) are in touch with the cold helium of about 250 °C from the main circulator. The cold helium enters the reactor core and flows through the pebble bed while it is heated up to 700 °C, then the hot helium flows through the hot gas duct and enters the steam generator. The heat is transferred to water in secondary circuit while the helium gas is cooled down to 250 °C. The cold helium enters the main circulator, and flows then along the inner wall of the steam generator vessel and flows into the outer coaxial pipe of the hot gas duct and enters the reactor pressure vessel where the partial cold helium is used to cool the wall of the reactor pressure vessel.

A series of strict measures of quality insurance and quality control are taken in the pressure vessel design and manufacture process. In-service inspection will be carried out during the pressure vessel service period, therefore, the accident of rupture of the pressure vessel is not considered in the accident analyses of the HTR-10.

## 4. Passive removal of the decay heat

The main heat transfer system is composed of the primary helium circulator, steam generator and feed pump, steam turbine, and circulating water system. During normal shut down operation the primary helium circulator would be running and the core decay heat would be transferred to the start up and shut down system through the steam generator, and then be removed by the circulating water system.

In the accident of loss of coolant and depressurization the main heat transfer system would become ineffective, thus, no core cooling is foreseen at all, decay heat will dissipated via the core structure by means of heat conduction and radiation to the outside of the reactor pressure vessel, where a cavity cooler is installed on the wall of the concrete housing cavity. It is connected with the air coolers on the top of the reactor building. This system works on the principle of the natural circulation of water and takes the decay heat via the air coolers to the atmosphere. In the HTR-10 two trains of passive decay heat removal system are installed and one of them has 100% capacity of decay heat removal.

The core diameter of HTR-10 is small and the average power density is low, therefore, for an accident of depressurization the maximum fuel temperature will be more or less that of the normal operation condition; this is due to the passive of decay heat removal. Even in the extreme condition of the failure of the two trains of the cavity cooler, the decay heat of the core could be dissipated through the wall of reactor concrete and the maximum temperature of fuel elements would be below the temperature limit of 1600 °C. In fact, the cavity cooler of the reactor concrete housing cavity is also designed for cooling the vessel and its support; it will keep the temperature in the allowable range.

The monitoring of operation conditions and surveillance for cavity cooler are maintained to realize the necessary operation conditions.

## 5. Two independent reactor shutdown systems

HTR-10 has two independent reactor shutdown systems: one is the control rod system and the other is the small absorber ball system. They are both placed in the side graphite reflector and are able to bring the reactor to cold shutdown conditions.

The control rod system consists of 10 control rods and their driving apparatus, which are composed of a step motor, a gearbox, a chain-chain wheel, a speed restrictor, and a rod position indicator. Each control rod consists of five individual sections held together by articulated joints. Each section is an annulus formed by 1Cr18Ni9Ti coaxial cladding tubes. The absorber material in the form of sintered $B_4C$ rings is filled in the annular space between two coaxial tubes. The total length of the control rod is 2750 mm including the absorber length of 2435 mm. On demand, the control rods are driven by the step motor and chain–chain wheel and can drop into channels of the side reflector by means of gravity.

The small absorber ball system is designed as the second reactor shutdown system, so-called the standby shutdown system. The basic principle is that when the rods do not drop, the small absorber ball system can be used for the reactor cold shutdown to keep it at sub-critical condition.

Small absorber balls are used for the second shutdown system. The small absorber balls in a diameter of 5 mm are sintered graphite balls mixed with 25% $B_4C$. Seven ball storage tanks, in which the small absorber balls are stored in operation conditions, are installed on the upper support plate above the upper reflector and connected with seven slotted channels of $160 \times 60$ $mm^2$ cross-section to the side reflector. On demand the plug the motor pulls out covering a hole on the bottom for each storage tank and the balls in the seven storage tanks drop through the holes into the reflector channels by gravity. A pneumatic suction system is used to return the absorber balls from the reflector channels to the storage tanks one by one before the reactor can be restarted.

Owing to the strong negative temperature reactivity coefficients, the turn-off of the main helium circulator, which then causes the reactor core to heat up, is sufficient to stop the chain reaction.

## 6. The barrier of confinement

In any accidents of the HTR-10 the maximum temperature of the fuel elements could not exceed the temperature limit and a significant radioactivity release can be excluded. In addition, the low free uranium content of fuel elements, the retention of relative radioactivity by graphite matrix of fuel elements, and the negligible activated corrosion products in the primary coolant system will maintain the radioactivity of the primary coolant system at a very low level. In the depressurization accidents of the primary coolant, the impact of radioactivity release on the environment will be insignificant. Therefore, it is not necessary to provide containment for the HTR-10.

Therefore, a confinement without requirement of pressure-tightness is adopted. The concrete compartments, which house the reactor vessel, the steam generator vessel as well as other parts of primary pressure boundary are designed to be leak-tight, will function as the confinement. The confinement, together with the accident ventilation system, serves as the barrier against the release of radioactivity into the environment.

The functions of the confinement are defined as:

1. During normal operation conditions the exhaust system maintains the cavity of the concrete compartments at negative pressure to prevent the dissipation of radioactivity inside the cavity into the reactor building. Before emission via the chimney, the exhausted air is filtered to minimize the impact on the environment according to the ALARA principle;
2. In the depressurization accidents, after the pressure inside the cavity exceeds 0.1 bars above atmospheric pressure a repture disk in the exhaust pipe will be automatically opened. The air inside the cavity will not be filtered but will be directly released into the atmosphere via the chimney.

The design of the confinement is based on a principle of low risk release. For the severe accident of depressurization the release of radioactivity is classified as prompt release and delayed release. In the prompt release the gaseous fission products in the helium coolant and solid fission products deposited on the graphite dust will be brought into the atmosphere in company with the release of primary coolant. In this course the release of radioactivity could be in small amount. However, in the delayed release of the depressurization the additional fission products retained in the damaged coated particles and the graphite matrix of fuel elements, which are caused by the temperature increase in fuel elements, could be released. This release would last for several tens of hours. Therefore, the release through chimney without filtering at the early stage of depressurization would cause less impact on the environment.

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